Advances in MEMS Deformable Mirrors for Space Based Telescopes



Steven Cornelissen, Jason Stewart, Tom Bifano, Paul Bierden
Boston Micromachines Corporation

Mark Horenstein

Boston University - Department of Electrical Engineering

NASA SBIR PHASE I/II
Approved for Public Release by NASA per NPR 2200

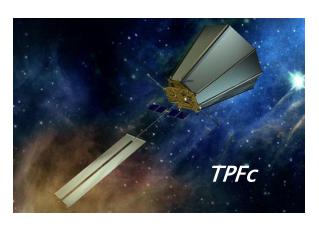


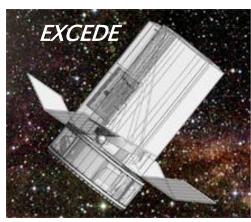
Outline

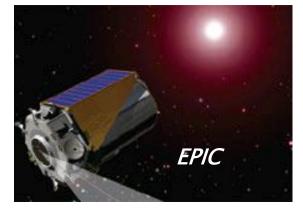
- DM Technology Overview
- Enhanced fabrication process developments for a 1021 segment tip-tilt-piston MEMS DM
- Low-power, Multiplexed Drive electronics development
- Enhanced Reliability DM systems for space based AO
- Preliminary space-qualification testing of BMC MEMS DM

MEMS DMs in Space Telescopes

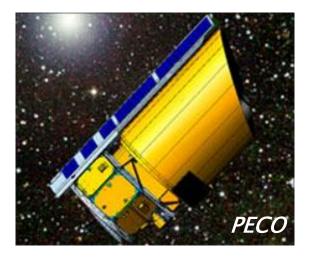
- Correction of static and slow moving aberrations in space-based optical imaging systems
 - High Contrast Imaging Instruments
 - Correction of surface figure errors in Light weight primary mirrors



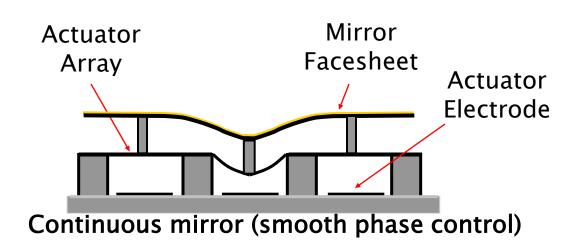




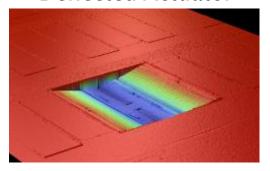




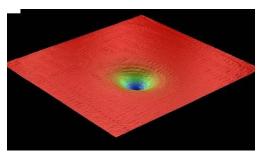
BMC Deformable Mirror Architecture



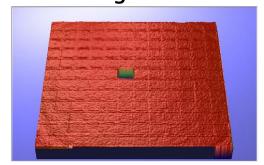
Deflected Actuator

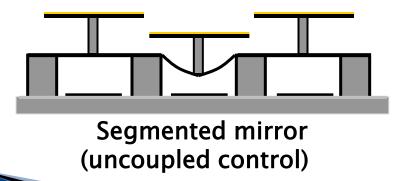


Deformed Mirror Membrane



Deformed Segmented Mirror





BMC Deformable Mirror Architecture

Actuator Array Mirror Facesheet

Actuator





Key Features of MEMS DMs

- Hysteresis-Free Electrostatic Actuation
- High Speed Response
- Scalable Large Actuator Arrays
- High Spatial Resolution Control
- Low Power Consumption
- Compact
- Batch Fabricated (1000s) low cost

Segmented mirror (uncoupled control)



BMC DM Commercial Product Family

MINI-DM

- 32 actuators (6x6 array)
- 1.5 2.3 mm aperture
- 1.5 5.5µm stroke

MULTI-DM

- 140 actuators (12x12 Array)
- 3.3 4.9 mm aperture
- 1.5 5.5 µm stroke

KILO-DM

- 1020 actuators (32x32 Array)
- 9.3 mm aperture
- 1.5 µm stroke





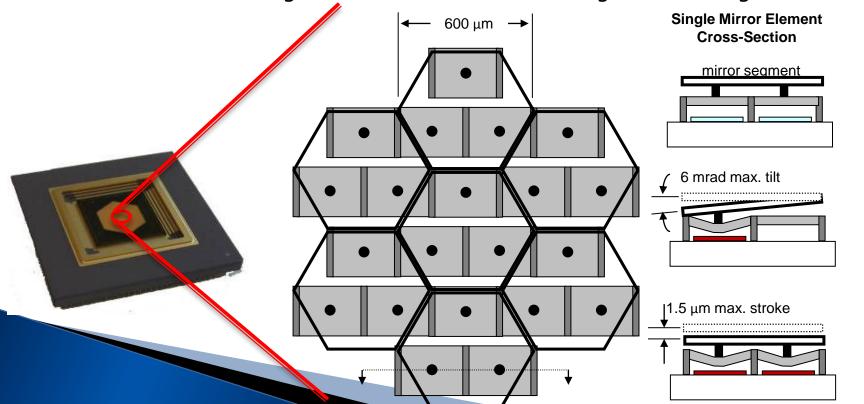


1021 Segment TTP DM Development



NASA SBIR PHASE I/II

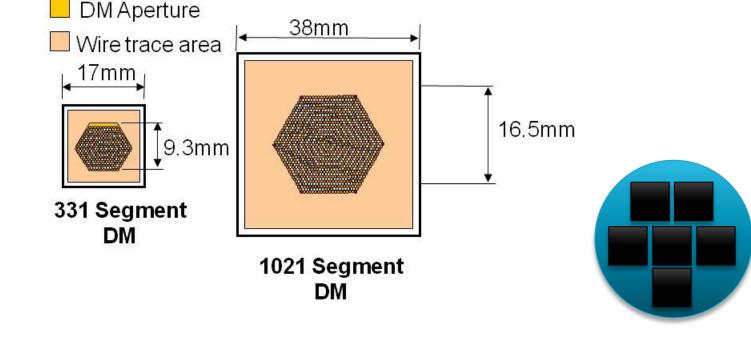
- Program Objective: Fabricate a 1021 segment (3063 actuators) DM
 - Extension of 331 segment DM developed in 2009
- Application: Visible Nulling Coronagraph
 - DM provides instrument with phase control using piston motion and amplitude control using tip-tilt motion
- Tip-tilt-piston degrees of freedom provided by three piston-only electrostatic actuators
- <10nm RMS mirror segment flatness achieved throughout full range of motion</p>

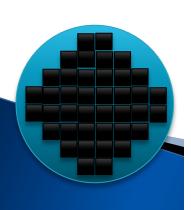


1021 Element Tip-Tilt-Piston MEMS DM



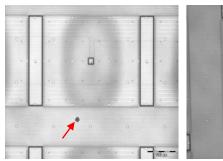
- Scale up mirror segments/actuators from 331/993 to 1021/3063
- Device architecture and fabrication process fundamentally scalable
- Challenge:
 - Managing inherent microscopic manufacturing defects (function of die area)
 - Controlling surface figure errors resulting from substrate bow and polishing

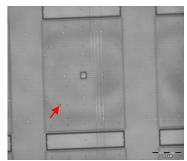






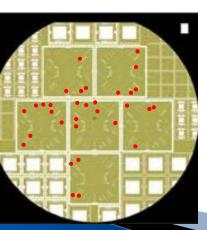




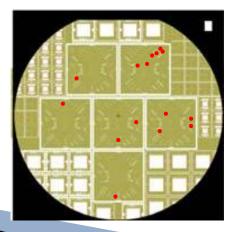


- Microscopic embedded particles are introduced during material deposition processes
 - electrical shorts (inactive/coupled actuators)
 - Surface figure defects
- Fabrication process improvements developed to reduce defect count

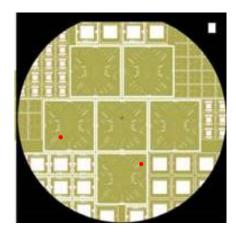
Wafer 24, Poly1 31 of 47 particles identified to cause killer defects



Wafer 2, Poly1
15 of 192 particles identified to cause killer defects



Wafer 12, Poly1
2 of 23 particles identified to cause killer defects

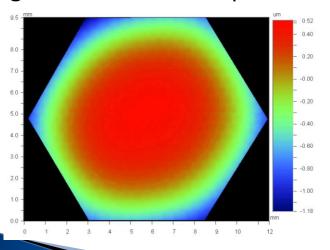


Large Aperture MEMS DM Surface Figure

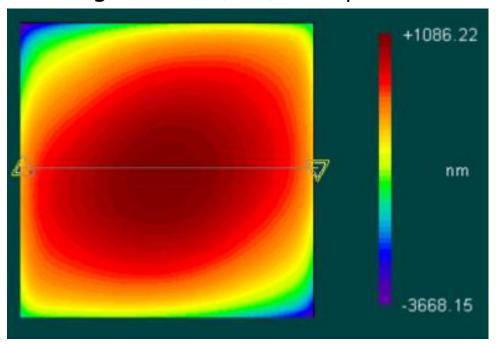


- Surface Micromachined devices conform to substrate figure
 - Imbalance of front and backside film thickness results on wafer bow
 - Wafer bow of 50m ROC typical at end of manufacturing process
- New thin film deposition processes developed to reduce wafer bow to 300m ROC

331 element DM Active Aperture figure error (P–V):~1 µm



4096 element DM Active Aperture Figure Error (P–V): ~3.5µm

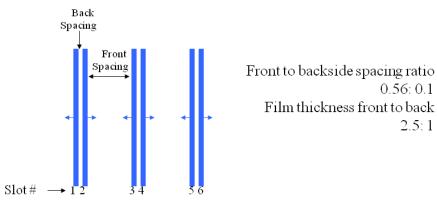




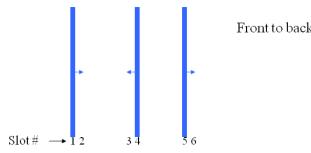
Reducing Unpowered Surface Figure

2.5:1

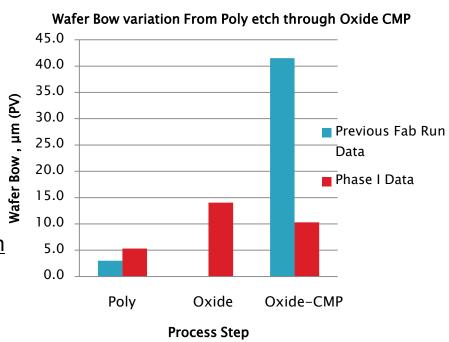
Standard wafer load pattern



Modified "Face-to-Face" single spaced load pattern



Front to backside spacing ratio 0.76: 0.56



Multiplexed DM Drive Electronics Development



NASA SBIR PHASE I/II

- Existing DM drive electronics using single DAC and amplifiers for each DM drive channel
- MEMS DM actuator is a capacitor most power consumed driving high voltage amplifiers & DACs
- Space-based platforms require low power, more compact, and light weight electronics

Existing MEMS DM Driver Specification

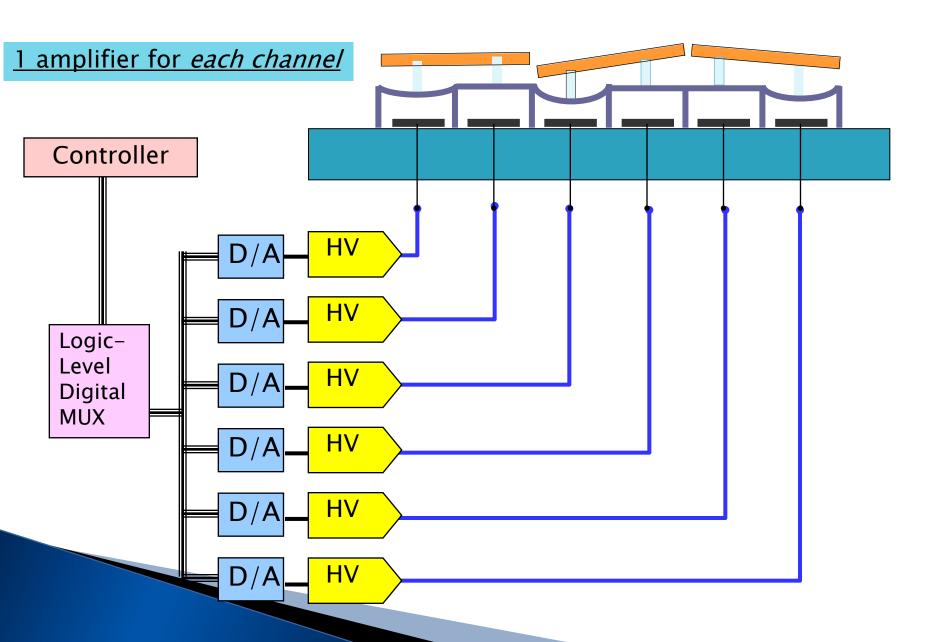
- # Channels: 4,096 channels
- Power Consumption: 80W (typ)
- Resolution: 14 & 16-bit
- Mass (w/ cables): 13.6kg
- Max Frame Rate: 24kHz
- Size: 3U Chassis (5.25" x19" x14")





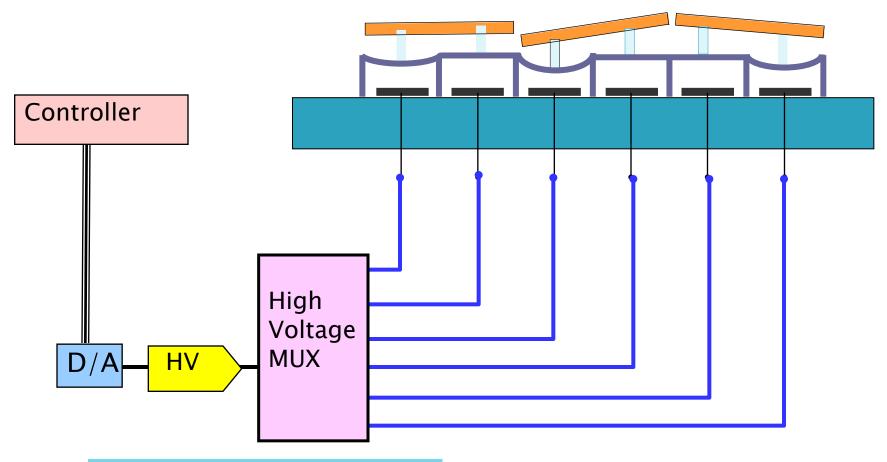
Heritage DM Drive Electronics Architecture





Multiplexed DM Drive Electronics Architecture

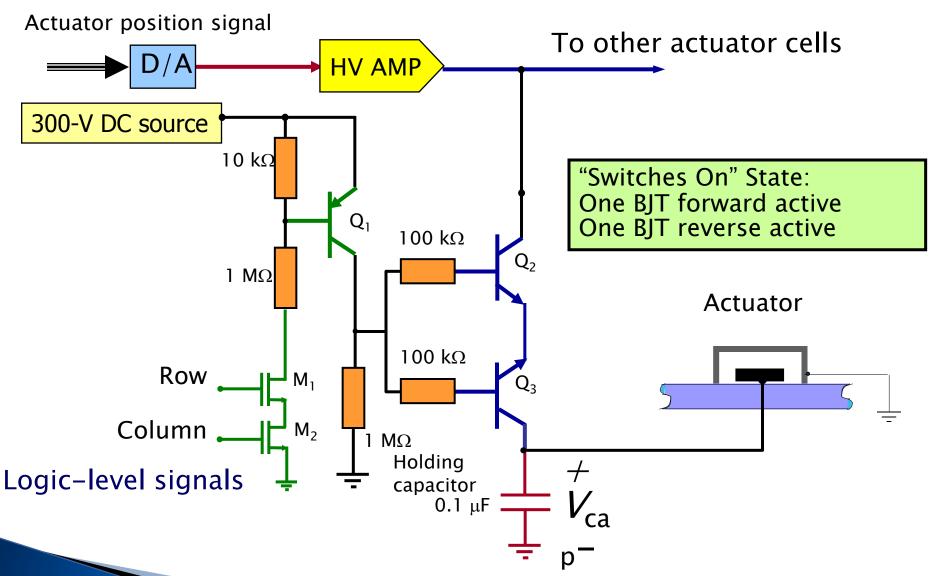




1 amplifier for entire system

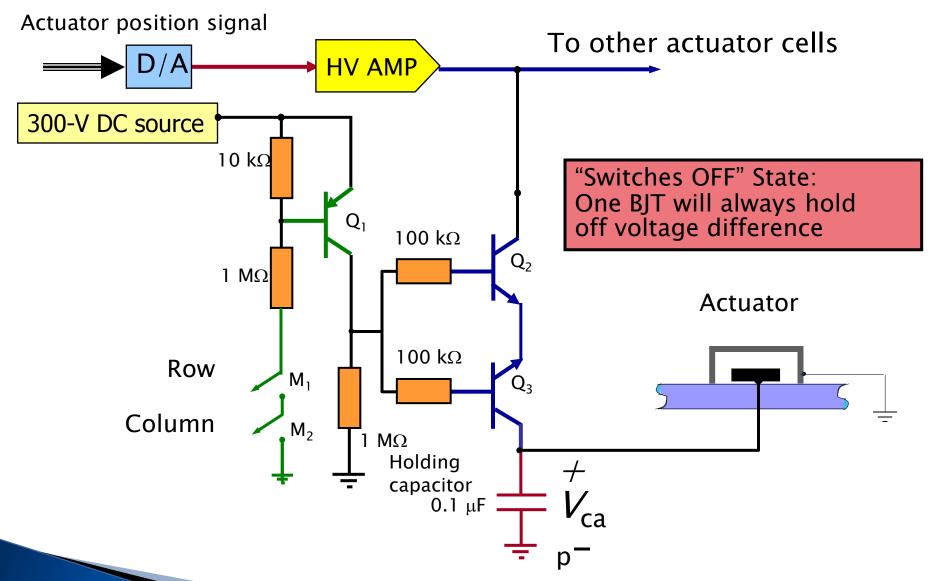
Multiplexed DM Drive Electronics Architecture





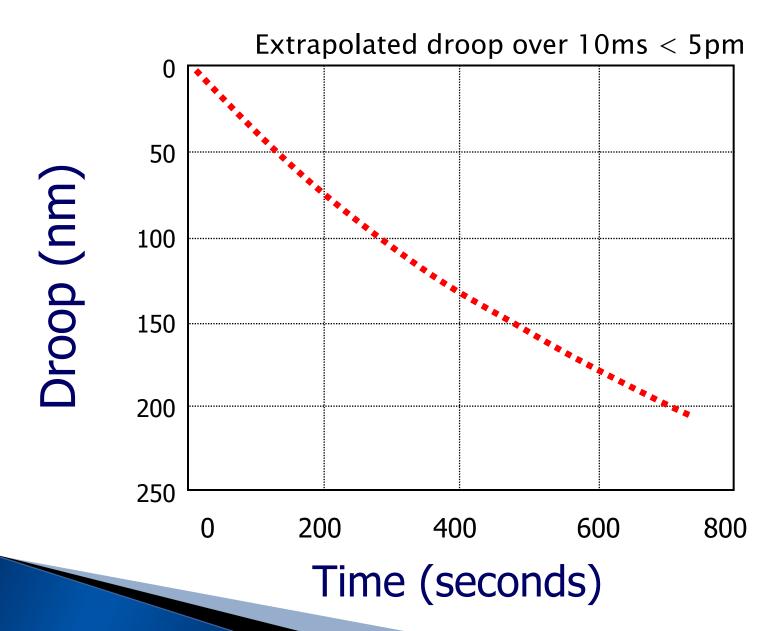
Multiplexed DM Drive Electronics Architecture





Driver Stability: Actuator Position (Droop) vs. time





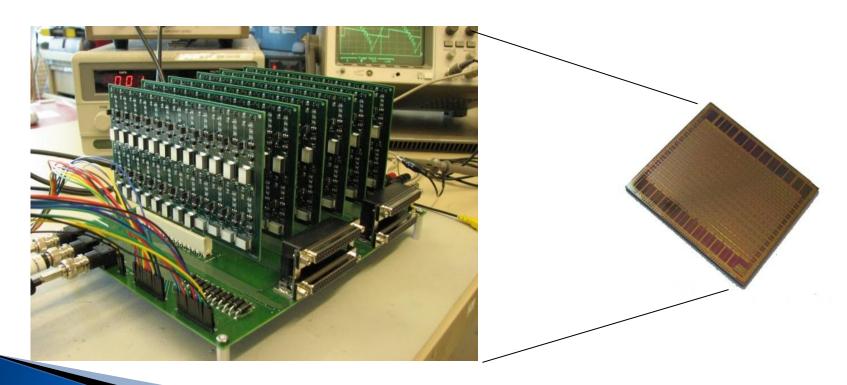
Power Consumption of 140 Channel Prototype Electronics



Driver Component	Low Power Test (Typical use)	High-Power Test (Extreme use)
Microcontroller (3.3 V)	25 mW	
High-Voltage Power Supply	22.5 mW (250 V × 90 μ A)	32.5 mW (250 V × 0.13 mA)
High-Voltage Amplifier		
Output Load	4.5 mW (150 V × 30 μ A)	600 mW (150 V × 30 μ A)
Quiescent Power	100 mW quiescent (250 $V \times 0.4$ mA)	100 mW quiescent (250 V \times 0.4 mA)
Total Power	152 mW	758 mW

Multiplexed Drive Electronics

- Prototype multiplexed drive electronics developed
 - 152mW power consumption (140 channels)
 - 16-bit resolution/<10pm step size
- Phase II will extend design to 3063 channels
- Integrate into HV ASICs for ultra compact form factor

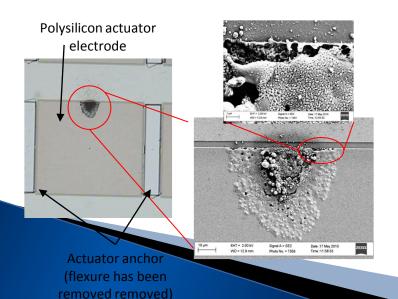


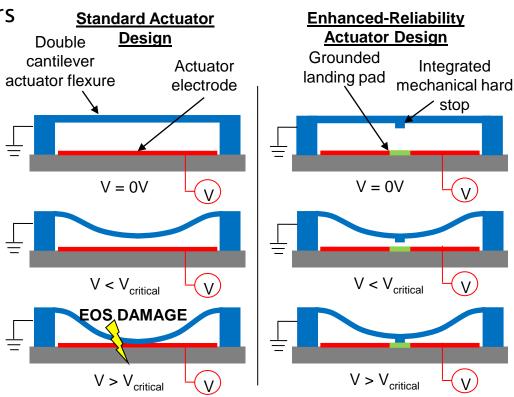
Enhanced Reliability DM Actuator Development



NASA SBIR PHASE I

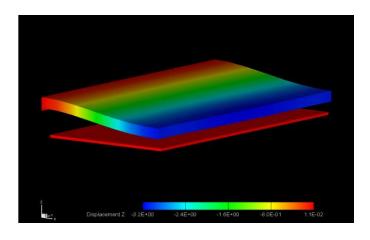
- Although MEMS DMs are highly reliable under normal operating condition the electrostatic actuators are sensitive to electronics faults
- Program Objective: Develop MEMS DM system tolerant of electronic over-stress (EOS)
 - Prevent irreversible failures due to actuator snap-through



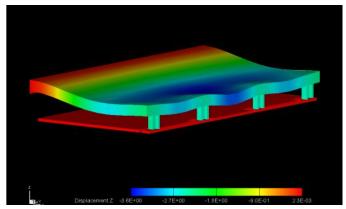


New Actuator Electromechanical Perfomance

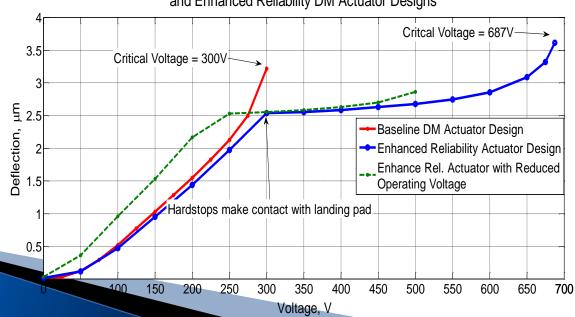
Baseline Actuator Design



Enhanced Reliability Actuator Design



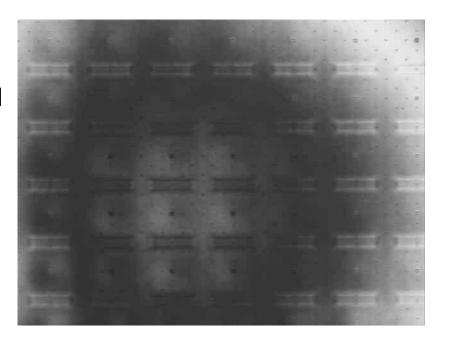
Electro-Mechanical Performance Comparison of Baseline DM Actuator and Enhanced Reliability DM Actuator Designs



Prevention of Snap-Through Related Damage



- Addition of current limiting elements further increases overall MEMS DM reliability
 - Eliminates high-current densities at snap-through

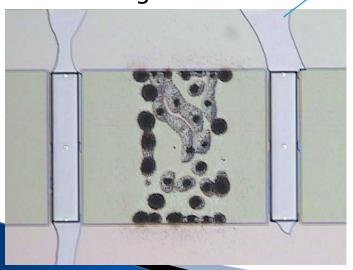


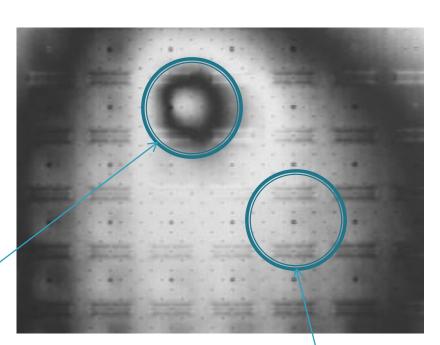
Prevention of Snap-Through Related Damage



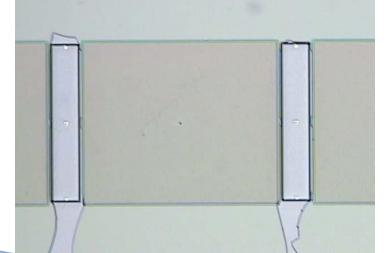
- Addition of current limiting elements further increases overall MEMS DM reliability
 - Eliminates high-current densities at snap-through

Without Current Limiting electronics





With Current Limiting electronics



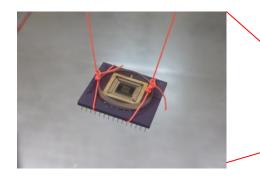
MEMS DM Space Qualification



- preliminary space qualification testing on BMC DMs on going at JAXA
 - Sequential Load testing
 - Acoustic
 - Random Vibration
 - Rapid Pump Down
 - Combined load testing
 - Cryo operation (5K)



Acoustic test





	DM:	BMC	DM	with	wind	low
--	-----	-----	----	------	------	-----

Temperature: ambient

Pressure: latm

Place: Tsukuba Space Center/JAXA

Acoustic level: please see the table above

▶ Time of acoustic load: 60(+2-0) second

 Conclusion: the DM survived! (no significant changes measured)

1/1oct center frequency	Acoustic pressure (dB)	torelance
31.5	128.0	+5/-10 dB
63	135.0	+- 3dB
125	139.6	+- 3dB
250	138.0	+- 3dB
500	135.0	+- 3dB
1000	132.0	+- 3dB
2000	129.0	+- 3dB
4000	124.0	+3-10dB
8000	118.0	+- 6dB
Over all	144.0	+- 2dB

* $0dB = 2x10^{-5}[Pa]$

Random Vibration Test



OdB	
Frequency (Hz)	PSD (G^2/Hz)
20	4.3
80	67.3
270	67.3
413	28.9
800	28.9
2000	2.5
Over all	21.1 Grms

- DM: BMC DM with window (same DM used for acoustic test)
- Pressure: latm
- Vibration level: -12dB, -6dB, -3Db, 0dB, +3dB (please see the table above to know 0dB)
- Direction of the vibration: only the vertical direction for the DM surface.
- Time of each vibration load: 60 second
- Conclusion: the DM survived! (no significant changes measured)

Thank You



Boston Micromachines Corporation is advancing MEMS deformable mirror technology to meet needs for spaced based Adaptive Optics systems through NASA's SBIR program

<u>Acknowledgements</u>

- Funding from NASA/JPL
 - SBIR Phase I/II # NNX10CE09P/NNX11CB23C
 - SBIR Phase I /II# NNX10CE08P/NNX11CB22C
 - SBIR Phase I # NNX11CF40P
- M. Horenstein at Boston University Photonics Center
- K. Enya, T. Kotani, S. Takeuchi at ISAS/JAXA



